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# **Improving Adaptive Video Streaming through Machine Learning**

By

**Anh Minh Le**

A Thesis

Submitted to the Faculty of Graduate Studies  
through the School of Computer Science  
in Partial Fulfillment of the Requirements for  
the Degree of Master of Science  
at the University of Windsor

Windsor, Ontario, Canada

2017

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# **Improving Adaptive Video Streaming through Machine Learning**

by

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January 19<sup>th</sup> 2018

## DECLARATION OF ORIGINALITY

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## ABSTRACT

While the internet video is gaining increasing popularity and soaring to dominate the network traffic, extensive study is being carried out on how to achieve higher Quality of Experience (QoE) in its content delivery. Associated with the HTTP chunk-based streaming protocol, the Adaptive Bitrate (ABR) algorithms have recently emerged to cope with the diverse and fluctuating network conditions by dynamically adjusting bitrates for future chunks. This inevitably involves predicting the future throughput of a video session. Predicting parameters being part of the ABR design, we propose to follow the data-driven approach to learn the best setting of these parameters from the study of the backlogged throughput traces of previous video sessions. To further improved the quality of the prediction, we propose to follow the Decision Tree approach to properly classify the logged sessions according to those critical features that affect the network conditions, e.g. Internet Service Provider (ISP), geographical location etc. Given that the splitting criterion will have to be defined together with the selection among ABR parameter values, existing Decision Tree solutions cannot be directly applied. In this thesis, some existing Decision Tree algorithm has been properly tailored to help learning the best parameter values and the performance of the ABRs with the learnt parameter values is evaluated in comparison with the existing results in the literature. The experiment shows that this approach can improve the performance of an ABR algorithm by up to 8.59%, with 98.38% of the testing sessions performing better than having a fixed parameter value, and only 0.8% performing worse.

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## LIST OF ABBREVIATIONS/SYMBOLS

QoE	Quality of Experience
ABR	Adaptive Bitrate
ISP	Internet Service Provider
VOD	Video-on-demand
BBA	Buffer Based Algorithm
AI	Artificial Intelligence
Geolocation	Geographical Location
OS	Operating System



# CHAPTER 1

## INTRODUCTION

Live Streaming and video-on-demand (VOD) are becoming the most popular methods to watch videos as the internet expands and gets more and more accustomed to our daily life. It was estimated that the entire video streaming market is worth of around US\$30.29 billion in 2016, and will grow up to US\$70.05 billion by 2021<sup>[1]</sup>. Youtube, with one of the most popular video streaming platform, reported that the consumption rate of mobile videos is rising 100% every year. Netflix reported that 10 billion hours of video was watched per month by its user base<sup>[2]</sup>.

In this growing market with a large number of competitors, improving Quality of Experience (QoE) for the users when they watch videos is a key factor for any publisher who wants to attract and retain its customers. From Livestream and New York Magazine's survey<sup>[2]</sup>, video quality was the most important factor for 67% viewers when they watch a livestream broadcast, and about 62% consumers are more likely to have a negative perception of a brand name of a company who has the video content delivered with low-quality.

It is, however, not an easy task to improve video quality, because there are many factors that contribute to the users viewing experience. According to a survey by JWplayer in 2016, the users are considering many factors that affect their QoE with a streaming service, with 24% considering that re-buffering ratio is the most important factor of their experience, and about 12% thinking that average bit rate, which is linked directly to the quality of a video, is the most important part, and another 12% saying that the most important factor is the time for a video to get started<sup>[3]</sup>.

With QoE being such an important factor to the user's experience, which have a direct impact on the revenue of the video streaming companies, researchers have proposed many different techniques to improve the QoE for the viewer, with their focus varies from dealing with the buffering and the bitrate selection, to handling many other aspects of the video streaming process. To demonstrate that their proposed techniques perform well, the implementation needs to be tested with a large variety of different settings of the users, ranging from different Internet Service Provider (ISP), different devices used for video streaming, different geographical locations, to different internet speeds etc. To deal with this problem, one of the possible ways is to formulate such impact from different users' conditions into the program parameters of the ABRs, and try to find the best values for these parameters for each future session to be run. However, most, if not all, of the existing ABR algorithms come with a set of default parameters that have been tested to suit a majority of the user base and are not catered to individual users. In the present thesis, we present our data-driven approach to determining ABR parameters. We have modified some existing Decision Tree Machine Learning algorithm in order to predict the best values of the parameters. With this approach, we can achieve a QoE increase of up to 8.59%, with around 98.38% sessions yielding better results than using the traditional method of choosing one parameter set for all sessions.

## CHAPTER 2

### PRELIMINARY WORK

In order to better explain the ultimate goal of the present thesis, first we introduce the key terminologies and give a brief introduction on how video streaming works. Then we will give a brief overview of recent approaches to improving the QoE of the video viewers.

#### 2.1/ Video Streaming, how does it work?

Video Streaming, by definition, is the act of streaming a video over the internet from a server to the user. From a more technical perspective, it is a constant data stream of a video kept downloaded to the user's device until either the data has been completely downloaded or the user has stopped watching. With the internet growing and video streaming getting more popular, many techniques have been developed in order to bring the best video streaming quality to different users. Video content now are usually partitioned into small chunks of a few seconds each [4]. Each chunk has many different versions stored on the server, encoded with different bitrates. The bitrate is essentially the amount of data per second played on a video device. The higher the bitrate of a chunk is, the higher the quality of that chunk can be displayed to the user.

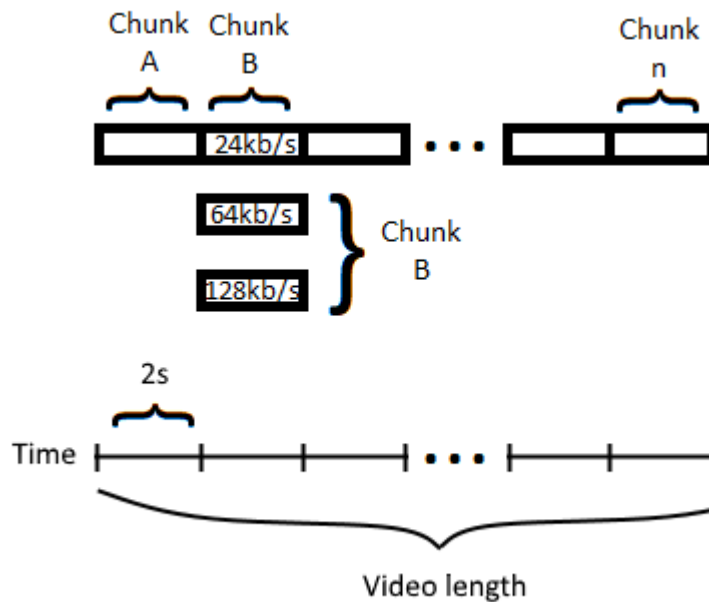


Figure 2.1: Model of video stored in server

The purpose of partitioning a video file into chunks like this is to make it easier to dynamically switch among different bitrates during a video streaming session. The necessity of switching among different bitrates on the go came from the fact that the internet download speed does not stay constant throughout an entire viewing session, which is defined by the period from the time the user starts watching a video to the time he/she stops watching it.

While a player can download in a second more than a second of video data, within that same time, the user will only be able to watch one second of the video. Hence, all the chunks downloaded but not yet played are saved in a buffer on the client side. Buffer size is the maximum amount of data or video chunks a client can hold at a time. It can be calculated using either the number of bytes or the number of seconds. We consider the model where a video player will not start playing a chunk until it has been completely downloaded, and will not download the next chunk until a space big enough for an entire chunk is available in the buffer.

In regard to the user experience, there are some terminologies that need to be explained [5]. The first one is start time, or join time, which is the period from the time when the user clicks on a video for viewing, to the time when the user actually starts watching the video. Usually this amount of time is used for the play buffer to get loaded with a few initial chunks. From the user's viewpoint, the lower this time is, the better. The second is re-buffering time, which is the total amount of time the video gets stopped or frozen in the middle of a playing session when the play buffer becomes empty, and the viewer has to wait for the player to download a new chunk of video. Similar to join time, the less this occurs, the better. The third is average bitrate, which is the average of the bitrates of all the chunks in a video downloaded over an entire viewing session. This value indicates overall how good the video display quality is, and the higher this value is, the better. In addition to these three attributes that can be used to determine the QoE, there are some other QoE metrics, for example: the number of times re-buffering happens, the number of times bitrate changes etc. Each ABR algorithm is designed with a different focus on different aspects of QoE, so there's no universal unique formula to define QoE. For the purpose of this thesis, we will mainly consider join time, re-buffering, and average bitrate.

## **2.2/ Related Work**

In this section, we will give a brief overview of different ABR algorithms and the related techniques proposed in the literature for improving QoE for the video viewers, discuss what parameters set by the authors can be improved to suit each individual user, and how it is related to the problem we will look into in this thesis. To start with, we need to understand what ABR algorithms are. Adaptive Bit-Rate algorithms, or ABR, is the name of a group of algorithms that deals with changing the bitrate of a video dynamically while a video viewer is watching, according to his/her current network conditions. For example, when someone experiences freezing (rebuffering), ABR algorithms will try to lower the bitrate. When someone has a good internet

condition while viewing a low bitrate video, ABR algorithms will try to increase the bitrate of that video.

There exist many different approaches to ABR algorithms. In An Optimized Stall-Cautious Adaptive Bitrate Streaming Algorithm for Mobile Network [6], the author divided ABR algorithms into three main classes: rate-based algorithms, buffer-based algorithms and optimized streaming algorithms. For rate-based class, ELASTIC [7] is a good example. ELASTIC is a client-side algorithm using feedback control theory to construct a single controller that will throttle the video level (bitrate) to fill up the buffer to a set buffer length to ensure the video playback will not have re-buffering. In its formula for the controller:

$$\dot{q}(t) = -k_p q(t) - k_i q_I(t)$$

$q(t)$  and  $q_I(t)$  are different states of the buffer, and  $k_p$  and  $k_i$  are 2 parameters of the controllers that are set to 0.01 and 0.001 respectively by default as proposed by the author of this paper.

For buffer-based class, we have Buffer Base Algorithm (BBA) [8] which uses the buffer state of the client's video player to choose the bitrate of the video. BBA proposed to set up a few parameters: the reservoir, upper reservoir and an  $f(B)$  function which determines the relationship between the bitrate and the buffer state in this algorithm (see figure 2.2).

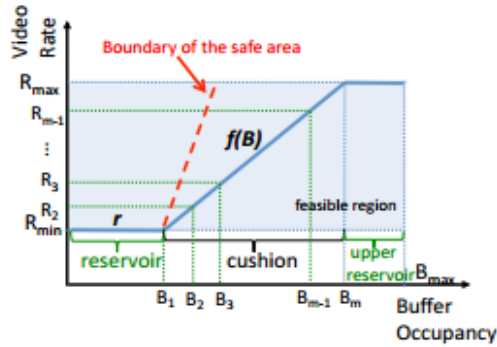


Figure 2.2: Buffer Base Algorithm model

During the 1<sup>st</sup> iteration of this algorithm BBA-0, the default parameters proposed by the author are set so that the reservoir size is 90 seconds, cushion is from 90 to 216 seconds (126 seconds) and the upper reservoir is 216 to 240 seconds (24 seconds) out of the total of 240 seconds buffer size. In other words, the reservoir size is 37.5%, upper reservoir is 10%, and the rest is for cushion. A more in depth look at BBA will be given in chapter 3.

In the optimized streaming algorithm class, we have MPC algorithm [9]:

```

1: Initialize
2: for  $k = 1$  to  $K$  do
3:   if player is in startup phase then
4:      $\hat{C}_{[t_k, t_{k+N}]} = \text{ThroughputPred}(C_{[t_1, t_k]})$ 
5:      $[R_k, T_s] = f_{mpc}^{st}(R_{k-1}, B_k, \hat{C}_{[t_k, t_{k+N}]})$ 
6:     Start playback after  $T_s$  seconds
7:   else if playback has started then
8:      $\hat{C}_{[t_k, t_{k+N}]} = \text{ThroughputPred}(C_{[t_1, t_k]})$ 
9:      $R_k = f_{mpc}(R_{k-1}, B_k, \hat{C}_{[t_k, t_{k+N}]})$ 
10:  end if
11:  Download chunk  $k$  with bitrate  $R_k$ , wait till finished
12: end for

```

Figure 2.3: Video adaptation workflow using MPC

which is based on the assumption that network condition should be reasonably stable and do not change too drastically within a short period of time. With that assumption, we can try to look  $N$  steps ahead and solve a specific QoE maximization problem. Within this algorithm, the look-ahead window  $N$  is a parameter that can be changed to suit each individual user better. It's worth noting that in this case, while a larger window size  $N$  is usually better, it will also negatively impact the runtime of the algorithm thus making the algorithm not being able to work efficiently at runtime. It's also worth noting that through the research reported in CS2P [10], we know that some key features such as ISP and geographical locations do have serious impacts on the network condition of a client, and thus can be used to improve the ABR performance on future sessions.

Last but not least, we need to introduce Machine Learning and more specifically, Decision Tree. Machine Learning is an application of artificial intelligence (AI) that provides systems the ability to automatically learn and improve from experience without being explicitly programmed [11]. Within the available machine learning techniques, one of the most commonly used is Decision Tree, which is a very specific type of probability tree that is constructed from a training set of data and can be used to make a decision about some kind of process [12] by tracing a set of conditions.

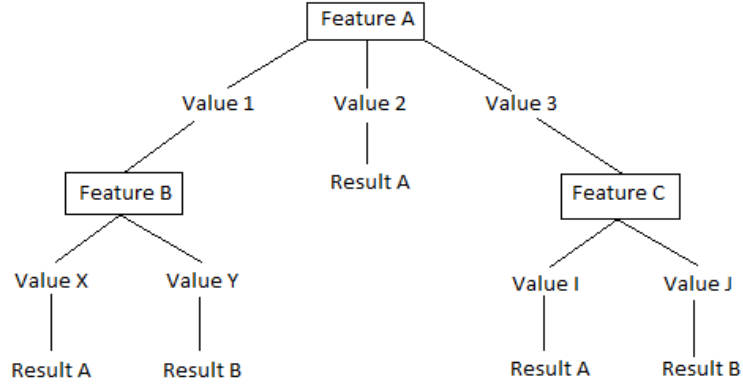


Figure 2.4: Decision Tree example

There are different approaches to constructing Decision Trees, including binary split, where at each node, the tree can only be split into two branches, and multi-way split, where at each node, the tree can be split into as many branches as the number of values the chosen feature has [13]. A feature chosen to be a splitting criteria usually is determined based on how much information gain can be obtained by choosing the considered feature to split the current node. There are also different approaches to dealing with the data that was not present in the decision tree, with the two popular approaches: (i) the technique used in C4.5<sub>[14]</sub> by putting the new value into all the branches and give each vote from each branch a weight based on how many instances are present in that branch. For example, if we have 2 branches with 100 instances and 50 instances respectively, the vote got from going down the 1st branch will be given a weight of  $1/1.5$ , while the vote got from going down the 2nd branch will be given a weight of  $0.5/1.5$ . (ii) the technique used in CART<sub>[15]</sub> by putting the new value into the branch with the most number of instances [16].

In the present thesis, we propose to follow the data-driven approach to use the key features to optimize those default parameters present in existing ABR algorithms so that they can have better setup for each individual session. Those key features will be used in selecting criteria/feature when implementing our modified Decision Tree for classification.

## CHAPTER 3

### PROBLEM STATEMENT, SOLUTION AND ALGORITHM

#### 3.1/ Problem Statement

Having reviewed different ABR algorithms and techniques used to improve QoE, we come to the realization that the parameters in each algorithm are usually fixed by the authors based on testing the algorithm on a large set of data with different user cases and choosing a set of parameters that fit well with the users in general. However, it is easy to see that not all users have the same viewing condition. Different users have different internet conditions affecting their video viewing experience in many ways, leading to some having a vastly different viewing experience compare to others who watch the same video on the same server. From the study in CS2P, we learned that the key factors that impact the user's viewing experience are the user's conditions such as ISP, geographical location, and device model.

Stemmed from that observations, we can easily see that: should we want the existing ABR algorithms to serve the user in a better way, the algorithm itself should be adapted to each user cases. To do that manually is inefficient, so we turn to Machine Learning for help with this problem. With Machine Learning, the computer itself can learn what kind of parameters are most suitable for each user and adjust the algorithm accordingly. The key issue here is that in many classes, we have a wide variety of possible values. For example, for ISP, we have Bell, AT&T, Verizon etc. We choose to use Decision Tree in order to quickly go through a new user's setting and retrieve the suitable parameters setting based on previously learned user cases. However, we cannot directly apply the Decision Tree algorithms, due to the following major issues:

- Decision Tree is usually used for classification problem with only two classes: true and false, and in our case, while we can call our problem classification, the parameters set we have are not limited to two.
- The best parameters set for each node and leaf can change when a node is split.

So, we will need to modify the Decision Tree algorithm to best suit our need for this case. In this chapter, we will look more into the problem with the normal Decision Tree algorithm and how we make a modification to it.

Before we present our work on the decision tree, we will explain how an ABR algorithm performs under normal condition with the default parameters proposed by the author, how the algorithm can be improved and whether the change in parameters make a significant impact on the QoE or not. In order to do so, we have chosen Buffer Based Algorithm (BBA) as an example. First, we need to understand exactly how BBA works and how we can modify its parameters.

### 3.2/ BBA algorithm

BBA algorithm, proposed by Te-Yuan Huang, Ramesh Johari, Nick McKeown, Matthew Trunnell and Mark Watson, is a result of collaboration research between Stanford University and Netflix Inc. to develop an ABR algorithm that depends solely on the buffer condition on the client side to dynamically change the video bitrate for a better QoE for the users of Netflix. The idea of the algorithm is very simple: with a predefined setting of the 3 parameters, i.e. reservoir, upper reservoir and an  $f(B)$  function which define the cushion area, the ABR algorithm will then only need to look at where the current value of the buffer fits into the predefined setting, and set the bitrate for the next video chunk accordingly as shown in figure 2.2.

In the 1<sup>st</sup> iteration of this BBA0 algorithm, as the algorithm was designed with a long video viewing sessions in the Netflix platform in mind, the buffer size is also set to a very large value of 240 seconds, with the reservoir size set to 90 seconds, cushion from 90 to 216 seconds, and the upper reservoir 216 to 240 seconds. In other words, the reservoir size is 37.5%, upper reservoir is 10%, and the rest is for cushion. For example, when the buffer has only 40 seconds of video left, the BBA algorithm will set the bitrate of the next video chunk to the minimum available bitrate; when there are 220 seconds of video currently downloaded in the buffer, the algorithm will keep the bitrate to the maximum; when the buffer length is between 90 to 216, the algorithm uses function  $f(B)$  to calculate a suitable bitrate value accordingly.

Now let us consider what will happen when we change the parameters of this algorithm. If the reservoir is set to a bigger size, the ABR will prefer the bitrate to be at minimum, which will definitely help dealing with the re-buffering problem, but will also make the average bitrate of the video relatively low. For the  $f(B)$  function, if the slope is too high, the bitrate will fluctuate too much with even a slight change in the buffer. The algorithm prefers the maximum bitrate, which, while increasing the overall average bitrate of the video sessions, will more likely to increase re-buffering time. If the slope is too low, it may decrease the average bitrate of the video sessions and the ABR will not respond to the change in the buffer fast enough.

Note that we actually do not need to keep track of three separate parameters: reservoir, function  $f(B)$  and upper reservoir. Keeping track of the reservoir and the slope of the function  $f(B)$  would be enough for the BBA algorithm to determine the bitrate to choose from, based on the current buffer state. Note also that BBA was designed with a large buffer size to work with long video viewing sessions. Our data set, which we will explain in chapter 4, consists of shorter video sessions. So we will be using a smaller buffer size and as such, the default parameters from the BBA-0 algorithm need to be converted into percentage and then converted to the new values for our smaller buffer size. By default, the reservoir consists of 37.5% of the maximum buffer size and the slope value can be set to: *the bitrate range available for a video* divided by 52.5% of the buffer size.



We have followed the BBA0 algorithm on backlogged traces in the data set to get the average bitrate and rebuffering ratio of each session. But with multiple QoE metrics, it is hard to tell directly how each session performs compared to others, so we will be converting those values into a single QoE value. As stated in chapter 2, there is no predefined unique QoE calculation formula. As such, in this thesis, we will be using QoE formula defined in the following way:

$$QoE(r, s, p) = \frac{r * rebufRatio(s, p) + 1}{AvgBitRateRatio(s, p)}$$

Here  $r$  is the weight of the rebufRatio, set to 20 by default. This weight  $r$  is used to express how much we want to emphasis on the rebuffering in our QoE formula. Should we want the rebuffering to have a larger role, we increase  $r$ , and should we want the rebuffering to be considered with less priority, we decrease  $r$ .  $s$  is session id.  $p$  is the parameter value used in the BBA0 algorithm to calculate this QoE.  $AvgBitRateRatio(s, p)$  is the average bitrate of session  $s$  with parameter value  $p$  over the maximum bitrate available. For example, if the  $AvgBitRate$  is 2300kb/s and the maximum possible bitrate is 2500kb/s,  $AvgBitRateRatio$  will be 2300/2500 or 0.92. The  $rebufRatio(s, p)$  is the rebuffering Ratio of session  $s$  with parameter value  $p$ . With this formula, the lower the QoE, the better, as QoE will decrease as the  $AvgBitRateRatio$  rises, and increase as the rebuffering ratio rises.

With the baseline of how BBA0 performs, we can now move on to change the parameters of the BBA algorithm, in order to see how such changes affect the algorithm. There are two parameters we can change: the reservoir and the slope. The change in either one will give us a different QoE value. So, we can have a table of QoE values from different parameter sets. It's worth noting that for some session with a low throughput rate, it will yield a lower QoE value no matter what parameter value is chosen. In order to have the QoE values comparable among all sessions, we normalize the results by using the normalization formula below, and Table 3.1 shows some sample results.

$$normQoE(r, s, p) = 1 - \frac{QoE(r, s, p) - \min\{QoE(r, s, p_i) | p_i \in P\}}{\max\{QoE(r, s, p_i) | p_i \in P\} - \min\{QoE(r, s, p_i) | p_i \in P\}}$$

Here  $P$  is the set of all different parameter values we use for BBA0.  $p_i$  is a parameter value within  $P$ . Recall that the lower the QoE value we have, the better. So, we need to reverse the order using  $1 - x$  in the formula.

Before:

ISP	Geolocation	...	QoE1	QoE2	QoE3
Bell	Windsor		6	5	4
Rogers	London		2	3	1

After:

ISP	Geolocation	...	QoE1	QoE2	QoE3
Bell	Windsor		0	0.5	1
Rogers	London		0.5	0	1

Table 3.1: Normalization example

Now with all the QoE values normalized, we need a way to compare QoE result from one parameter set with the one from another parameter set. The way we choose to do this is to take average QoE of all the sessions obtained from applying this parameter set, using normQoE formula. With that, we can know which one is the best QoE set currently. The reason why we need to know this is that this would be the parameter set that would be chosen when we want to select a parameter value for the entire user base as it gives the best QoE value according to our QoE formula. More details about this will be given in chapter 3.3. The best parameter set calculated from this method will be used as our base value to compare with the result we obtained after running Machine Learning in order to see how much Machine Learning can improve this value even further.

$$QoE(r, S, p) = \frac{1}{|S|} \sum_{s \in S} QoE(r, s, p)$$

$$SingleBestQoE(r, S) = \max\{QoE(r, S, p_i) | p_i \in P\}$$

$$normQoE(r, S, p) = \frac{1}{|S|} \sum_{s \in S} normQoE(r, s, p)$$

$$SingleBestNormQoE(r, S) = \max\{normQoE(r, S, p_i) | p_i \in P\}$$

Here S is a set of sessions. QoE(r,S,p) is QoE of a single parameter set p value throughout set S, and SingleBestQoE(r,S) is the best QoE(r,S,p<sub>i</sub>) for all p<sub>i</sub> taken from parameter set within P. We have the same 2 formula with the same purpose for normalized set as well.

### 3.3/ Comparing parameters set

For the first part of this thesis, we want to propose a way to systematically compare different parameters set to each other. As stated in the previous section, for our testing, we are only looking to compare the average bitrate and rebuffering ratio between each data set comprised from different parameters set. We can then obtain a table of data of different parameters set with different results that will look like table 3.2:

Parameters set	1	2	3	4
AvgBitrate	2000kb/s	3000kb/s	4000kb/s	2500kb/s
Rebuffering Ratio	0.01%	0.5%	0.8%	0.5%

Table 3.2: Comparing parameters set

Through some initial testing, we found out that with different parameters set being tested, usually what we obtain is a tradeoff between average bitrate and rebuffering ratio, because when average bitrate goes up, the rebuffering ratio usually goes down, and vice versa. So with that observation, it is difficult to say that one parameters set is better than every other set unless both the average bitrate and rebuffering ratio get improved. As the higher the average bitrate the better, and the lower the rebuffering ratio the better, we can define that a parameters set  $i$  producing the result  $avgBitrate_i$  and  $rebuf_i$  is better than parameters set  $j$  that produces the result  $avgBitrate_j$  and  $rebuf_j$  if and only if  $avgBitrate_i \geq avgBitrate_j$  and  $rebuf_i \leq rebuf_j$ .

$$(avgBitrate_i, rebuf_i) \geq (avgBitrate_j, rebuf_j) \\ \Leftrightarrow avgBitrate_i \geq avgBitrate_j \ \&\& \ rebuf_i \leq rebuf_j$$

In any other case, if only one of the two values increases and the other decreases, it became a tradeoff and that trade off might be desired in certain user case, so we can leave the choice of which one to choose up to the one who uses this. So for example, if we look at table 3.2 again, parameters set 2 is undoubtedly better than parameters set 4 as the average bitrate of set 2 is better and their rebuffering ratio is the same. As for set 1 and 3, we cannot say conclusively any of them is better: if the user values rebuffering more, they can go with set 1 with a slight trade off in average bitrate; and if the user values average bitrate more, they can go with set 3 with a trade off in rebuffering ratio instead. The way the user can define which one they want is through many factors, including the QoE formula. As stated in the previous chapter, there's no unique single QoE formula being used by everyone, so by fixing a single QoE formula for a certain use case, we can then look at the table and define one single best parameters set that gives that QoE formula the highest value. In our case, as we have defined our own QoE formula in chapter 3.2, we can also find our own

single best parameters set that is suitable to our need and that will perform better than other parameters sets according to our QoE formula.

One example of another factor that can change the definition of single best parameters set is the way we normalize the data. What we are doing right now is local normalization where we normalized the data within each session (locally), but on the other hand, we also have global normalization. Global normalization works by taking into consideration the entire data set instead of just within each session. For example, consider the following table 3.3:

Parameter set	1	2	3
Session 1 QoE	1	15	20
Session 2 QoE	5	1	20
Session 3 QoE	20	19	20
Session 4 QoE	20	19	20
Session 5 QoE	20	19	20
Total	66	73	100

Table 3.3: Example data set (Lower is better)

If we were to use local globalization, the best parameters set will be set 2 as after local normalization, we have the result look like this:

Parameter set	1	2	3
Session 1 QoE	1	0.26	0
Session 2 QoE	0.79	1	0
Session 3 QoE	0	1	0
Session 4 QoE	0	1	0
Session 5 QoE	0	1	0
Average	0.358	0.852	0

Table 3.4: Local normalization (Higher is better)

With this, we can see that parameters set 2 is the best one as most of the sessions prefer set 2. However, if we were to use global normalization, we got table 3.5:

Parameter set	1	2	3
QoE Session 1	1	0.263	0
QoE Session 2	0.789	1	0
QoE Session 3	0	0.053	0
QoE Session 4	0	0.053	0
QoE Session 5	0	0.053	0
Average	0.358	0.28	0

Table 3.5: Global normalization (Higher is better)

With this, parameters set 1 become the best one instead of parameters set 2. But as we have talked about in this chapter, global normalization and local normalization are just other ways to define a different single best parameters set, which comes with its own tradeoff. Global normalization focuses more on the betterment of the overall average QoE, and is willing to sacrifice/allow more sessions to have worse QoE as long as the total average QoE increases, while local normalization focuses more on the betterment of the number of sessions that perform better, and is willing to sacrifice/allow the overall average bitrate to become worse. If we think about it in term of the user, global normalization allows for the happy customers to become happier at the cost of more unhappy customers, while local normalization allows for more happy customers to exist at the cost of the already happy customers become slightly less happy. So local and global normalization therefore are just different ways to choose the best QoE. Out of the two, we choose to go with local normalization for our testing as our goal with the decision tree is more in line with the advantage that local normalization offers.

In the next chapter, we will discuss how we can improve the result even further using Decision Tree learning.

### 3.4/ Decision Tree Training

First, let's recap on how normal Decision Tree works. Decision Tree is used to classify data, usually into two groups per step, each of them being a class, which is defined based on a training data set provided. From the root of the tree, which is the node that contains all the training data set, the Decision Tree algorithm will go over all the features of that dataset and try to find which feature is the best to be used to split the data set into two (for binary split) or multiple subsets (for multiway split). The way Decision Tree algorithm defines the best feature is according to which feature gives the best information gain across all the split sets, or in other word, lowest entropy among all the split sets. Here, entropy is a measure of the randomness in the information being processed [17], or we can call it the impurity of a dataset.

$$Entropy = - \sum_i p_i (\log_2 p_i)$$

That's how a normal classification decision tree works, but in case the response are continuous values instead of categorical ones, we also have another subclass of decision tree called Regression Tree, which splits the data according to the minimum Mean Squared Error of the child nodes after being split by a feature.

$$MSE = \frac{1}{N} \sum_{i=1}^N (\bar{y} - y_i)^2$$

When a data set is split, if a split child has most of its data belonging to a same class, the entropy of the said child will be low. Thus, the information gain is high, and the feature is preferred over other available features. The tree will stop splitting once one of the stopping criteria is meet. These include: (i) the number of instances in a node is too small; (ii) the depth of the tree is too high; and (iii) all values of all child nodes are of the same class. Once a full tree was constructed this way, the Decision Tree can aid in the process of classifying a new data to determine whether it belongs to this class or the other by going down the tree with the feature of the new data. Should the new data that are being classified have a feature value not used or are new to the decision tree, there are two popular approaches to this, either (1) put all new data down to the child node with the highest number of instances, which is used in CART; or (2) put the new data down to all the child nodes with a weight proportional to the number of instances of each child, which is used in C4.5. CART and C4.5 are two popular decision tree algorithms.

Now we will explain how to apply the decision tree in our setting. A normal Decision Tree technique cannot be used directly on our data set due to several reasons. First, while our problem can be called a classification problem, we have more than 2 classes to choose from, with each of them being a different parameter set used by the ABR algorithms. Second, while the parameter set that a single video viewing session prefers is fixed, the parameter set for all the sessions within the same group might not. For example, let's look at table 3.6:

Session	ISP	Country	City	Device Model	OS	QoE1	QoE2	QoE3
1	Bell	Canada	Windsor	PC	Window	1	1	0.6
2	Bell	Canada	Windsor	Mobile	Android	0.9	1	0.5

Table 3.6: Sample Table 1

Consider the two sessions in the table 3.6. Session 1 prefers both parameter set 1 and 2, while session 2 prefers set 2. If these 2 sessions are grouped together at the current node, since most of their feature are the same, the preferred parameter set for this node will be 2 as it yields the best QoE overall for all sessions in the node. However, should the two sessions here be split further based on their device model or OS, the preferred set for the node with session 1 could be 1, while the preferred set for the node with session 2 will be 2.

So, our first challenge is to find a way to find out which feature will be the best for splitting, now that entropy and information gain formula does not work due to the changing classification and multiple classes. To do this, we look back at the definition of entropy as well as the regression tree and see how we can apply it to our new problem. What we found out is that, in our problem, what we want is the best parameter set within a group of sessions to have the normalized QoE value of that parameter set being 1 or as close to one as possible. For example, look back at table 3.6. The best parameter set is 2 because both session 1 and 2 have their QoE value of the parameter set 2 being 1. So, we can say that the group is “pure” because all the QoE values of the best parameter set are 1s, and its “impure” when not all of the QoE values of that best parameter set is 1. Let’s look at table 3.7:

Session	ISP	Country	City	Device Model	OS	QoE1	QoE2	QoE3
1	Bell	Canada	Windsor	PC	Window	1	1	0.6
2	Bell	Canada	Windsor	Mobile	Android	0.9	1	0.5
3	Bell	Canada	Toronto	PC	Window	0.7	0.8	1

Table 3.7: Sample Table 2

By adding session 3 into the table, the best parameter set for all 3 of them is still set 2 since it has the highest average QoE, but not because the QoE value of session 3 is 0.8. Session 3 by itself actually prefers set 3 over set 2 even though set 2 is good enough. In this regard, we define a new impurity formula to determine how good a group of sessions is, from the MSE formula:

$$parIndex(r, S) = \underset{i}{arg} \max \{ normQoE(r, S, p_i) | p_i \in P \}$$

$$Impurity(r, S) = \frac{1}{|S|} \sum_{s \in S} (1 - normQoE(r, s, p_{parIndex(r, S)}))^2$$

$parIndex(r, S)$  is a formula to define which parameter set is the best overall parameter set for all sessions in  $S$ , and with that value, we can find the Impurity of the set  $S$  with the Impurity formula.

With this formula, if all the QoE of the parameter set is 1, the impurity will be 0, or we can say that the set is pure, meaning all sessions in that set prefers the same parameter set. Every other QoE value will increase the impurity of the set by a degree measured by the distance from 1, and what we want is for the impurity to be as low as possible.

Now that we have a way to define which feature is better for splitting, we move on to discuss the splitting criteria. As mentioned before, in a normal decision tree, we usually have either binary split, which will always split a node into two child nodes, or multi-way split, which will split the node into multiple child nodes with all the values of that feature. For example, if we have a feature Weather with values Sunny, Rain, Snow, binary split will give us 2 child nodes: “Sunny and not Sunny” or “Rain and not Rain” or “Snow and not Snow” while multiway split will give us 3 child nodes Sunny, Rain and Snow. Unfortunately, with our specific problem of dealing with the video viewing sessions, neither approach is suitable as the number of values in each feature is too large. With our data set of around 8700 session (more details will be given in chapter 4), we have more than 1700 different ISP. So if we were to do binary split, the depth of the tree will be too high with no noticeable gain while increasing the cost of running through all combination of these 1700 ISP with different features, making the time complexity of the algorithm reaching  $O(n^2)$  where  $n$  is the total number of all feature values. On the other hand, if we were to do multiway split, the tree becomes a really shallow but wide one with each leaf having a very small number of sessions. This would easily lead to overfitting, which is a problem happened when a Machine Learning algorithm gets trained to fit a specific training set too much that it won’t work on any different testing set. To deal with this problem, we have changed the way Decision Tree split the nodes with a trade-off between binary split and multiway split. Note that with the number of parameter set  $M$  acting as classes, after we do multiway split, even though we can have up to 1700 different child nodes, they all choose one of the  $P$  parameter sets as their best/preferred parameter set, and they will have impurity either equal to 0 or larger than 0. At this point, we combine all child nodes, after each multiway split, that choose the same parameter set so they can be split later on should a better feature be found to split them. Thus, the minimum number of child nodes per parent node will be 2 while the maximum will be  $2P$ , two for each of the  $P$  different parameter sets, one for impurity equal to 0 (meaning they already reached “pure” and cannot be split anymore) and one for impurity larger than 0 (meaning they are “impure” and can continuously be split again).



With the way to split the data set defined, we can now complete the training part of our modified Decision Tree. To help with the process of creating the tree from the training set, we use two addition classes. The first is `treeNode`, which will hold the information of (i) which sessions are currently in this node, (ii) which node is its parent or child, (iii) how to get to the child, (iv) which parameters set is the best for all sessions in this group, and (v) the impurity of this node. The second is `sessionInfo`, which just holds all the information of a session including all its features, QoE value for each parameter set, and which parameter set has the best QoE value. To construct the tree:

Step 1: Put all the training sessions into 1 single `treeNode`, which will be the root.

Step 2: For every feature class we have, split the node using multiway split and combine all the impurity of all the child nodes using the following formula:

$$Impurity(r, \{S_1, S_2 \dots S_M\}) = \sum_{i=0}^M \frac{|S_i|}{|S|} * Impurity(r, S_i)$$

$$\forall i, j \leq M, S_i \cap S_j = \emptyset$$

Here M is the number of child nodes the current node S has, and  $S_i$  is a child node of S.

Step 3: If the combination of impurity from all the child nodes got from splitting the node using this feature is the lowest, and (i) there are at least 2 child nodes choosing different best parameter set, or (ii) one has impurity > 0 and one has impurity equal to 0, then this feature will be used to split this node. It will be added to the current node as Splitting Feature so we know that this node uses this feature to split.

Step 4: Combine all child nodes having impurity > 0 and having chosen the same best parameter set into one node, with the maximum number of nodes equal to the number of parameter sets. Also, combine all child nodes having impurity = 0 and having chosen the same best parameter set into one node, with the maximum number of nodes equal to the number of parameter sets. With this, the minimum number of child nodes a node can have will be 2, and the maximum will be 2\*number of parameter set.

Step 5: Add all the combined child nodes into the tree, while also adding the feature's value that was chosen to get to each child from the parent node so it knows which feature and value was chosen to go down to which child.

Step 6: Go through all the nodes in this current layer of the tree. If a node has impurity and has more than 10 sessions inside, repeat step 2 to 6 for this node. Otherwise, add 1 to the counter of leaf node for this layer. If the number of leaf nodes in this layer is equal to the number of nodes in this layer, or if the layer size is larger than 50, stop constructing the tree.

Step 7: Save the tree for use when testing.

It worth noting that in step 6, the layer size is limited to 50 so that in theory, the tree will not become too big which will have a harmful impact on the runtime of the algorithm. In practice, the tree usually only has around 10 layers.

### 3.5/ Decision Tree Testing

Now we will explain how to use the obtained tree on the testing set to see how well it performs. The testing follows these steps:

Step 1: Load the tree and the sessions in the testing set

Step 2: From the root, for each session in the testing set, go down the tree using the feature of the session.

Step 3: If the testing session has a feature value that the tree does not have, do one of the followings:

- Follow the technique used in C4.5: go down all the children of the current node and get a vote back from each child. Each child's vote is combined with the weight of that child which depends on the number of sessions per child.
- Follow the technique used in CART: go down the child with the most number of sessions.

Step 4: Record the prediction for each session in the testing set

Step 5: Calculate how much the Decision Tree algorithm has improved over selecting only the single best parameters set for the entire testing set, by using the formula:

$$PercQoEIncrease = \frac{SingleBestQoE(r, S) - DecisionTreeQoE(r, S)}{SingleBestQoE(r, S)}$$

Step 6: Find out how many sessions have improved QoE, have kept the same QoE or got worse QoE compared to only select one best parameters set for the entire testing set.

The result for the testing process will be discussed in chapter 4.

## CHAPTER 4

### DATASET, TESTING RESULT AND CONCLUSION

#### 4.1/ Dataset

To test our algorithm, we use a proprietary dataset from Conviva Inc. The dataset consist of 8411 sessions from 143 different countries. For each session, we have the measure of a sequence of actual network throughput along with the timeline of the session. Each session also came with all their features including different countries where the sessions were run, the different internet service provider (ISP) of the sessions, the device and OS the session was run on, etc. The list of features we considered and their total number of feature values are given in table 4.1.

Country	State	City	ISP	Connection	CDN	OS
143	432	1487	1724	9	2	5

Table 4.1: Data feature

In the 8411 sessions we have, although we have many different countries, most of the data are actually sessions occurred within North America, giving a high throughput rate, meaning that we do not actually have that many sessions that showcase what will happen when the throughput rate is low, such as rebuffering or that the bitrate needs to be lowered down. So in order to make the data reflect those cases more accurately we opted to do resampling [18], which is a technique commonly used in machine learning to deal with imbalanced dataset where data get skewed toward one side (like in our case where data is skewed toward the side with good throughput rate). There are two types of resampling: over-sampling where we add a random number of copies of instances (in our case, sessions) of the under-represented class, and under-sampling, where we remove instances of the over-represented class. In our case, due to the already small number of sessions we have at 8411, we choose to do over-sampling by selecting sessions with rebuffering in any of the parameters set and adding in a random number of no more than 20 copies of those, bringing the total number of sessions to 8650. This will only be done during the decision tree learning part. For the part on comparing parameters set, we will use the default 8411 sessions.

## 4.2/ Testing Result

For the testing, first, we begin by choosing parameters for the BBA-0 algorithm. To recap, the original value proposed by the authors of the BBA-0 algorithm gives us the reservoir value of 37.5% and the slope of 2213/12600, with 2133 being the range of bitrate we have (going from 196kb/s to 2409kb/s), and 12600 being the cushion time in ms. With those base values, we tried 5 different parameter set as described in table 4.2 by keeping one single slope and running 5 different reservoir values. Since we cannot have the bitrate jumping directly from the lowest to the highest bitrate, the cushion time must not approach 0. Also, since there must be enough space for the bitrate to reach maximum, the cushion time must not exceed (buffer size - reservoir size). Hence, with the default slope value, the cushion time must not exceed 150000ms. This area is denoted as the safe zone for the  $f(B)$  function in BBA algorithm [8]. The reservoir is also under the restriction that it cannot reach 100% as it will make the cushion time approach 0. Otherwise, the reservoir value can change freely.

Set	1	2	3	4	5	Original
Reservoir (%)	5	10	20	30	40	37.5
Slope	2213/ 100000	2213/ 100000	2213/ 100000	2213/ 100000	2213/ 100000	2213/ 126000
AvgBitrate	1996.412	1943.159	1838.201	1734.3	1630.949	1594.538
Rebuffering Ratio (*10000)	0.8%	0.5%	0.2%	0.17%	0.15%	0.16%

Table 4.2: Parameter sets value

So with this data and the definition we have in chapter 3.3, we can say conclusively that parameters set 5 is better than the original default parameters proposed by the authors of the BBA algorithm as both the average bitrate and rebuffering ratio of set 5 improve over the original set. However, that's not to say that all other parameters sets are not as good as the original one simply because they were not able to improve both of the values like set 5. Instead, they all showed a tradeoff to improve average bitrate more in exchange of worsening the rebuffering ratio.

As we can get result by changing only one parameter, it makes sense that we should also try to change both the parameters at the same time to see how much it can further improve the average bitrate and rebuffering ratio. So, for the next test, we do a combined change of both reservoir and slope, each with 7 different values including the original parameters set as one of the possible values, giving us 49 different sets as in table 4.3.

Set	1	2	3	4	5	6	7
Reservoir (%)	5	10	20	30	40	41.5	5
Slope	2213/60000	2213/60000	2213/60000	2213/60000	2213/60000	2213/60000	2213/80000
AvgBitrate	2103.2	2048.3	1941.1	1835.4	1731.4	1712.2	2048.3
Rebuffering Ratio (*10000)	1.02	0.54	0.25	0.18	0.16	0.16	0.84

Set	8	9	10	11	12	13	14
Reservoir (%)	10	20	30	40	41.5	5	10
Slope	2213/80000	2213/80000	2213/80000	2213/80000	2213/80000	2213/100000	2213/100000
AvgBitrate	1994.4	1888	1783.3	1679.8	1664	1996.4	1943.2
Rebuffering Ratio (*10000)	0.50	0.24	0.18	0.16	0.16	0.76	0.47

Set	15	16	17	18	19	20	21
Reservoir (%)	20	30	40	41.5	5	10	20
Slope	2213/100000	2213/100000	2213/100000	2213/100000	2213/120000	2213/120000	2213/120000
AvgBitrate	1838.2	1734.3	1630.9	1616.8	1948	1895	1790.2
Rebuffering Ratio (*10000)	0.24	0.18	0.16	0.16	0.71	0.42	0.24

Set	22	23	24	25	26	27	28
Reservoir (%)	30	40	41.5	5	10	20	30
Slope	2213/120000	2213/120000	2213/120000	2213/130000	2213/130000	2213/130000	2213/130000
AvgBitrate	1686.5	1583	1567.7	1923.7	1870.8	1766.4	1662.6
Rebuffering Ratio (*10000)	0.17	0.16	0.16	0.73	0.41	0.23	0.17

Set	29	30	31	32	33	34	35
Reservoir (%)	40	41.5	5	10	20	30	40
Slope	2213/130000	2213/130000	2213/140000	2213/140000	2213/140000	2213/140000	2213/140000
AvgBitrate	1558.8	1543.5	1898.7	1845.9	1741.7	1638.2	1415.4
Rebuffering Ratio (*10000)	0.16	0.16	0.70	0.40	0.22	0.17	0.16

Set	36	37	38	39	40	41	42
Reservoir (%)	41.5	5	10	20	30	40	41.5
Slope	2213/140000	2213/126000	2213/126000	2213/126000	2213/126000	2213/126000	2213/126000
AvgBitrate	1404.8	1932.7	1880.1	1775.7	1672.2	1568.5	1553.1
Rebuffering Ratio (*10000)	0.16	0.72	0.41	0.23	0.17	0.16	0.16

Set	43	44	45	46	47	48	Original
Reservoir (%)	37.5	37.5	37.5	37.5	37.5	37.5	37.5
Slope	2213/60000	2213/80000	2213/100000	2213/120000	2213/130000	2213/140000	2213/126000
AvgBitrate	1757.4	1705.7	1656.8	1608.9	1584.8	1560	1594.5
Rebuffering Ratio (*10000)	0.17	0.16	0.16	0.16	0.16	0.16	0.16

Table 4.3: 49 parameters set result

From this result table, if we take out the average bitrate and rebuffering separately, we got table 4.4 and 4.5. Looking at these tables, we can see a clear trend that, as the cushion and reservoir increase, the average bitrate becomes worse while the rebuffering becomes better. And among all of our parameters set, with the definition in chapter 3.3, we have set 17 and 18 both undoubtedly perform better than the original parameters set as both the average bitrate and rebuffering ratio of them improved compared to the original parameters set. Between set 17 and 18, we cannot say conclusively which one is better as set 17 has slightly better average bitrate (1631kb/s compare to 1617kb/s) and set 18 has slightly better rebuffering ratio (0.00001593 vs 0.00001598). Among the remaining parameters sets, we have set 46 and 47 performing worse than set 17 and 18 as they worsen in both average bitrate and rebuffering ratio. So those sets can be taken out of the table completely without affecting any future decision. The remaining parameters sets all perform better in one value while worsen in the other, so it can be left to the users to choose which one they want expressed by their QoE formula. For example, if they want to choose improvement of average

bitrate over the improvement in rebuffering ratio, they can choose set 1, 2, 7 or 8 as they all highly improve the average bitrate, trading off with a worse rebuffering ratio. And vice versa, if they want to choose improvement of rebuffering ratio over average bitrate, they can choose set 29, 30, 35 or 36 as they all improved the rebuffering ratio in exchange for worsen average bitrate.

Cushion\ Reservoir	60	80	100	120	126	130	140
5	2103	2048	1996	1948	1933	1924	1899
10	2048	1994	1943	1895	1880	1871	1846
20	1941	1888	1838	1790	1776	1766	1742
30	1835	1783	1734	1686	1672	1662	1638
37.5	1757	1706	1657	1609	1595	1585	1560
40	1731	1680	1630	1583	1568	1558	1415
41.5	1712	1664	1616	1568	1553	1544	1405

Table 4.4: Average bitrate across 49 parameters sets (higher is better)



Cushion\ Reservoir	60	80	100	120	126	130	140
5	1.02	0.84	0.76	0.71	0.72	0.73	0.7
10	0.54	0.5	0.47	0.42	0.41	0.41	0.4
20	0.25	0.24	0.24	0.24	0.23	0.23	0.22
30	0.18	0.18	0.18	0.17	0.17	0.17	0.17
37.5	0.17	0.16	0.16	0.16	0.16	0.16	0.16
40	0.16	0.16	0.16	0.16	0.16	0.158	0.157
41.5	0.16	0.16	0.16	0.16	0.16	0.157	0.156

Table 4.5: Rebuffering (\*10000) across 49 parameters sets (lower is better)

So from doing parameters set comparisons, we can already find many different parameters set that can either undoubtedly perform better than the original parameters set or allowing for some trade off to improve over the original parameters set according to different QoE formula. For the next step, we are going to improve that result even more by using Decision Tree. With the QoE formula defined as in chapter 3.2, we can then use the values in table 4.3 to calculate the QoE for each parameters set, and find out the best one among them to be our single best parameters set.

The 8650 sessions in our dataset were divided into a training set to train the decision tree and a testing set to be used for testing, at the ratio of 9:1. With the default weight in the QoE formula set to 20, and using the technique used in C4.5 algorithm (put the sessions with a feature that our tree does not have, into all the child nodes and get a vote from each of them with the weight, which is the number of sessions in each node), we got the QoE value increased by 8.59% compare to the single best set QoE, and if we want to take a look at each individual value, the average bitrate is improved 2.657% relative to the single best set average bitrate, while the rebuffering ratio is improved from 0.000389% to 0.000251%. It's worth noting that, because we have so little rebuffering to begin with, even with resampling, the increase in absolute value looks small in number. In relative value, the rebuffering ratio is improved by 35.4%. Out of 864 sessions in the testing set, we have 850 sessions (98.38%) get improved in QoE, compared to the single best

parameters set, 7 sessions (0.81%) perform the same, and 7 sessions perform worse compared to the single best parameters set. We also tried to use the technique used in CART algorithm (put the sessions with a feature that our tree does not have, into the child with the most number of sessions), and we found that the result is slightly worse, with QoE increased by 8.5% instead and average bitrate improved by 2.53%.

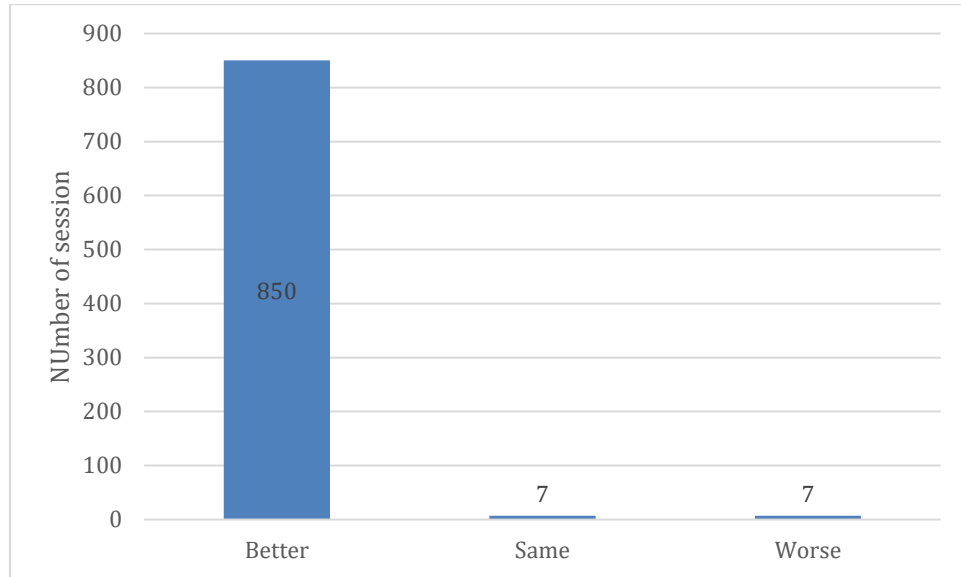


Figure 4.1: Ratio of better, same and worse QoE visualized

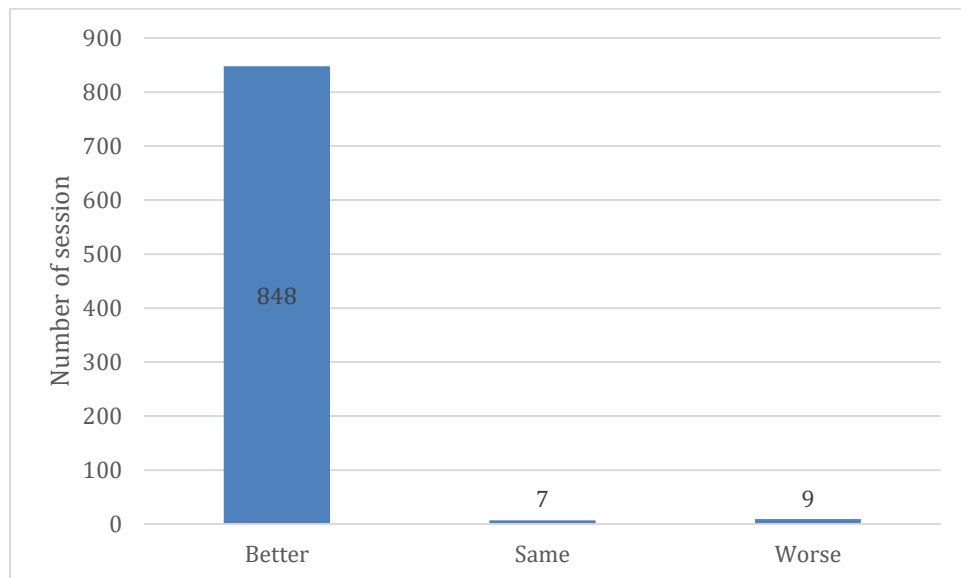


Figure 4.2: Ratio of better, same and worse AvgBitrate visualized

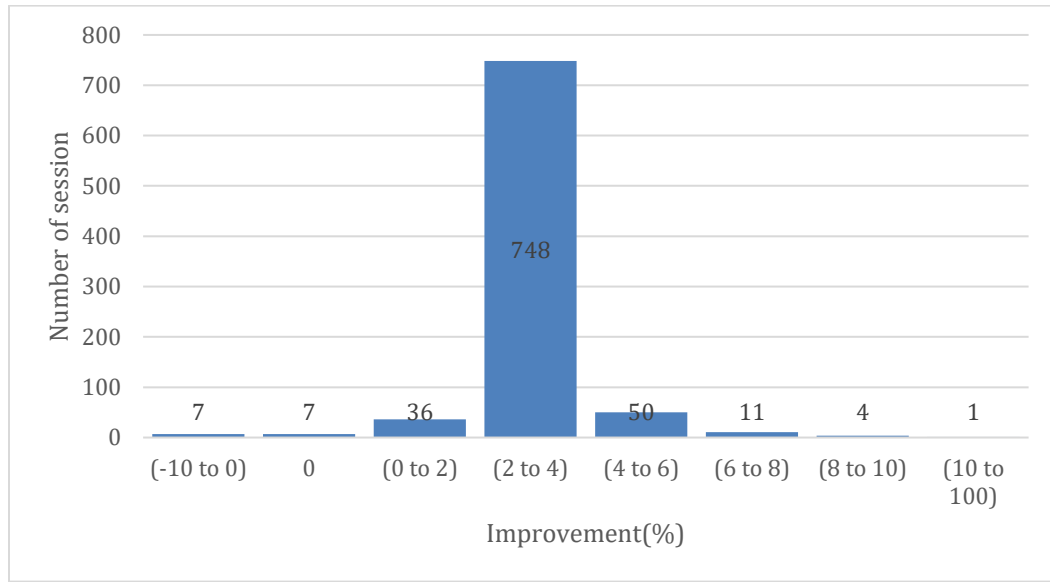


Figure 4.3: Session per percentage QoE increase comparison

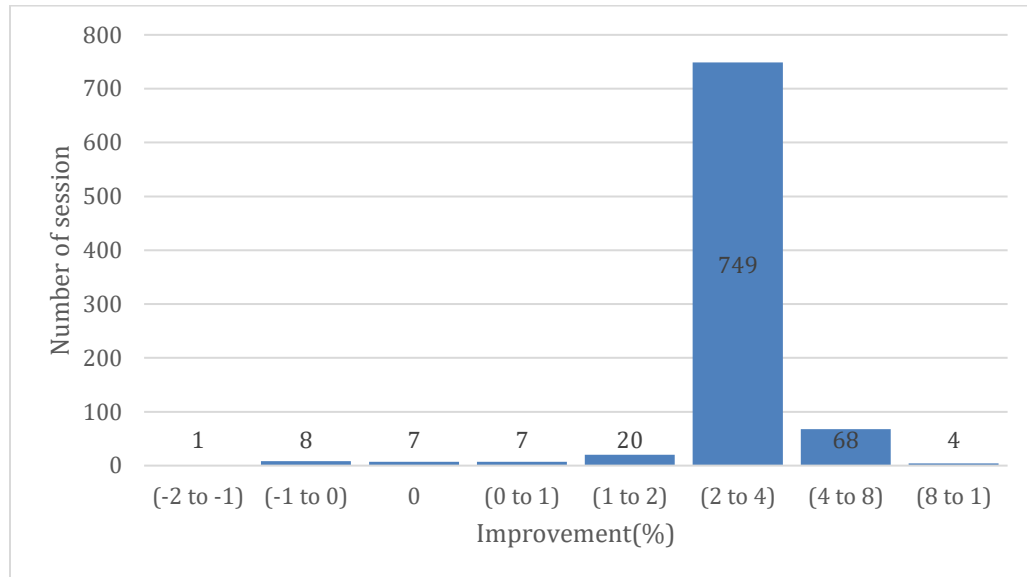


Figure 4.4: Session per percentage AvgBitrate increase comparison

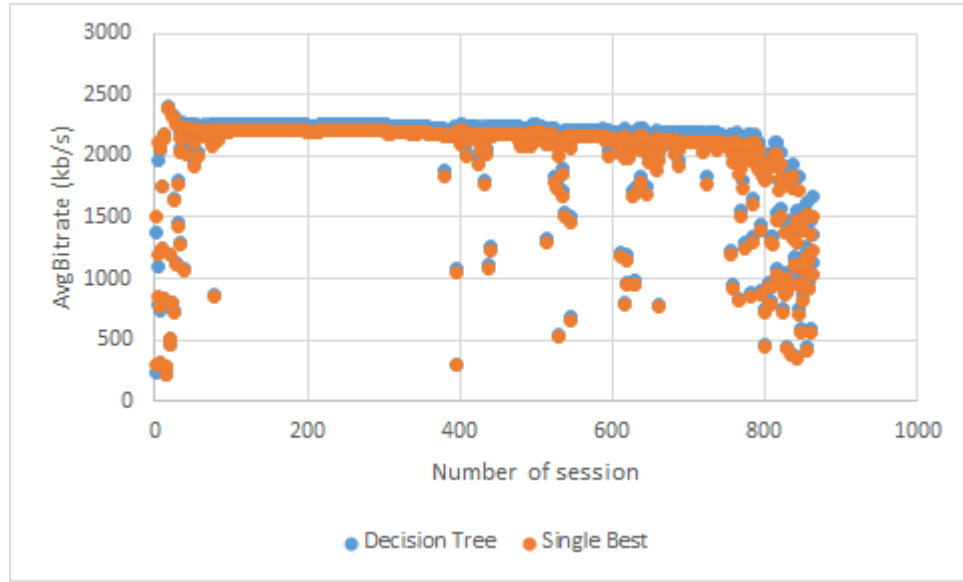


Figure 4.5: Average bitrate Decision Tree vs Single Best (Higher is better)

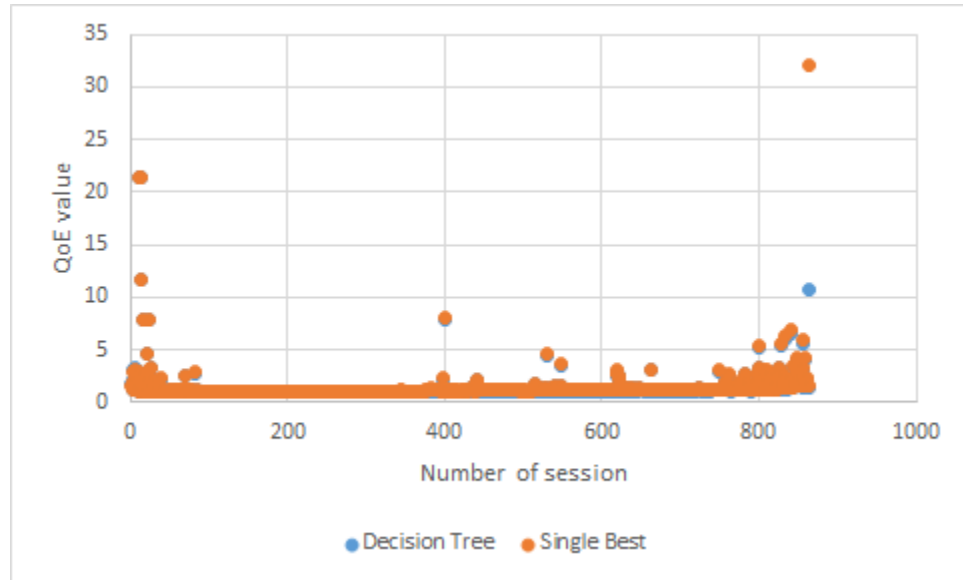


Figure 4.6: QoE Decision Tree vs Single Best (Lower is better)

In figure 4.5 and 4.6, it is hard to see how much the average bitrate and QoE improved going from single best parameters set to decision tree, so in figure 4.7 and 4.8 we show the cumulative distribution function of QoE and average between the two to show clearly which one is better.

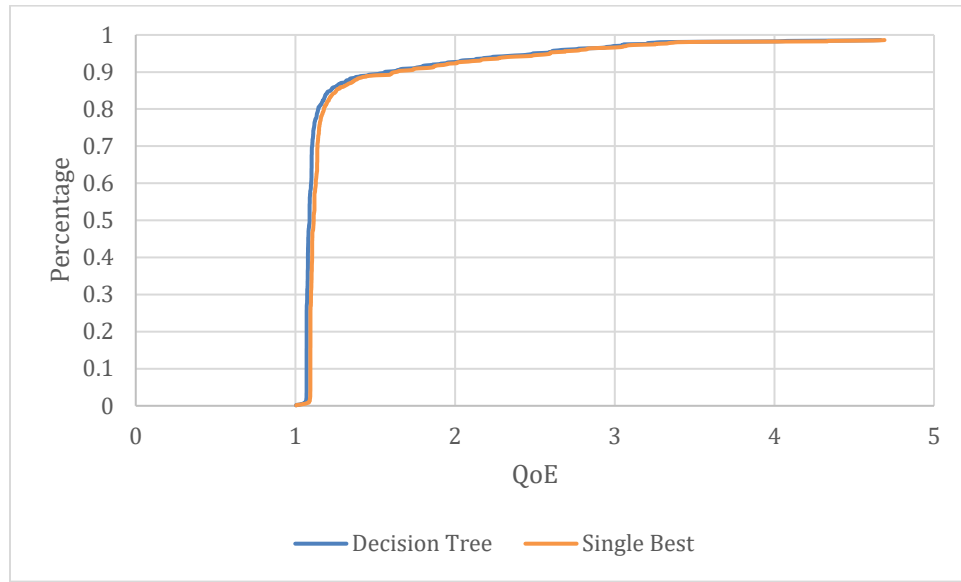


Figure 4.7: Cumulative Distribution Function of QoE (Lower is better)



Figure 4.8: Cumulative Distribution Function of Average Bitrate (Higher is better)

As among all of our testing sessions we only have around 20 sessions with rebuffering, in figure 4.9 we only look at the change within those 20 sessions.

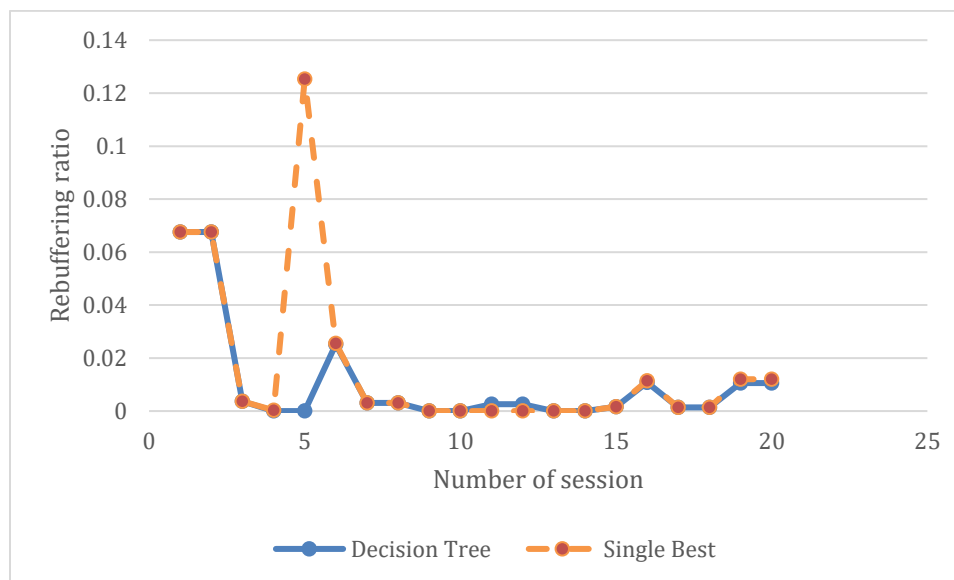


Figure 4.9: Rebuffering Decision Tree vs Single Best (Lower is better)

Looking at figure 4.3 and 4.4, we can also see that within 864 sessions we have for the testing set, most of them get increased in QoE and average bitrate from 2 to 4%. The worse one for QoE decreased the QoE by 9.5%, while the best one increased QoE by 66.9%. For the average bitrate, the worse one decreased by 21% from 291kb/s to 227kb/s while the best one increased by 10.6% from 1513kb/s to 1673 kb/s. With this result, we can make the conclusion that Decision tree can further improved the single best parameters set by allowing the sessions to change the parameters set to the a different one for each session.

We have talked about how the QoE formula is not unique and can be changed depending on the user requirement. So we want to test how the decision tree would work on our data set if we change the QoE requirement by varying the weight  $r$  in the QoE formula. We test on different weights in increment of 5 from 0 to 50, and the result we got is recorded in table 4.6:

QoE formula: $QoE(r, s, p) = \frac{r * rebufRatio(s, p) + 1}{AvgBitRateRatio(s, p)}$											
Weight r	0	5	10	15	20	25	30	35	40	45	50
QoE increase	0.062 %	3.53 0%	3.26 5%	2.32 9%	8.593 %	3.09 3%	6.68 4%	14.16 7%	17.8 40%	11.0 73%	15.74 0%
Avg BitRate increase	0.009 %	- 0.14 7%	- 0.07 5%	- 0.08 7%	2.650 %	2.69 7%	2.68 0%	8.703 %	8.54 0%	2.65 0%	8.550 %
Rebuf improvement (*10000)	- 0.3 %	10 %	4%	2.7%	1.4%	0.6%	17%	- 0.2 %	0.4 %	1%	- 0.1 %
Better (QoE)	0.460 %	2.07 0%	1.26 9%	1.27 0%	98.38 0%	98.7 34%	98.8 50%	99.42 1%	99.5 40%	98.0 00%	99.70 0%
Same (QoE)	99.30 0%	97.4 65%	98.2 69%	97.9 10%	0.810 %	0.57 0%	0.92 0%	0.231 %	0.46 0%	0.23 0%	0.230 %
Worse (QoE)	0.230 %	0.46 0%	0.46 1%	0.81 0%	0.810 %	0.69 0%	0.23 0%	0.347 %	0.00 0%	0.81 0%	0.000 %

Table 4.6: Result of different QoE formula's focus using technique in C4.5

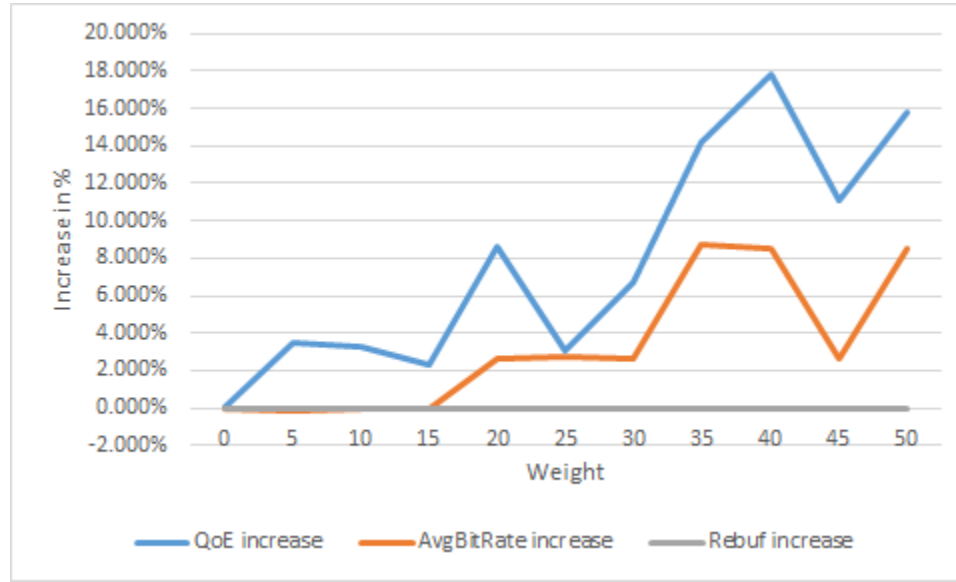


Figure 4.10: Decision Tree with different weight value

With the change in weight, we can see that when rebuffering time was not considered at all for the QoE formula, the Decision Tree algorithm only slightly improves the QoE value, average bitrate and slightly worsen the rebuffering ratio. Out of all the testing sessions, we only have 0.46% sessions performing better, 0.23% performing worse and the majority of sessions performing the same and this ratio continues as the weight increases up to 15. However, for the QoE value, according to figure 4.8, QoE improvement in general increases as the weight increases. The average bitrate also goes from *worse* to *improved* compare to the single best parameters set. Rebuffering in general has gone down as the weight increases. This is to be expected. The BBA algorithm actively pushes the average bitrate down to avoid any possible rebuffering. When we select the single best QoE for the entire dataset, we also have to take into account the rebuffering of the sessions, hence the overall average bitrate is low. However, once the data is learned via decision tree, each group of sessions can now freely choose a better average bitrate for their group without having to worry about other sessions in other groups holding it down due to rebuffering, so the bitrate in average increases as the weight increases. Starting from weight set 20 onward, we see that the ratio of sessions performing better stays relatively stable at around 98.8%, and the ratio of sessions perform the same also stays stable at around 0.6%. The ratio of sessions performing worse stays low at around 0.5% throughout all different weight values. With the above analysis, we can conclude that our Decision Tree solution performs well with stable results across different QoE settings, which means that it can be used by all video hosting services with different requirement and focus for their video streaming system.

Another result we can get with our proposed algorithm is related to its cost. The decision tree building and testing itself takes a relatively small amount of time, with the run time stay at only 4900-5000ms for tree building, and the testing took around 700ms on a desktop with an i7 gen 4.



The time consuming part comes from building initial QoE table by simulating the ABR algorithm itself: It takes up to 20000ms on the same machine. The runtime for machine learning part however does increase to 6700ms when running with more number of parameters set (49 sets), but because tree building only needs to be run once and the decision tree the algorithm built can be used for decision making at the start of any video viewing session, we do not have to worry too much about building time. As for the cost of space, the decision tree object is relatively small at only 770-800KB. However, the data used to build the tree takes much more space, at around 8MB for 7 different parameters set. While these data do not need to be kept after the decision tree is created, it is advised that these data be kept so that in the future, should there be more parameters set to be considered, and we do not have to reconstruct these data and can easily make a new decision tree with just the new data added in.

#### **4.3/ Future Work**

From what we learned in doing this thesis, in future, we can keep improving our algorithm by tackling these two problems: The first is in regard to the number of parameter set we have. We proposed 6 different changes to the reservoir and 6 different changes to the slope of the two parameters in BBA algorithm. Combining them together we have 36 different parameters set. It is easy to see how this number could increase exponentially if we have a large number of parameters or increase the number of values per parameter. For this problem, we hope to be able to look at the change within each single parameter only, and reduce the number of parameters that we should bring up for the combination test. For example, if in BBA algorithm, the reservoir changes do not improve the QoE of the algorithm much, we can remove the reservoir changes from our consideration and only focus on the slope to improve the QoE. Or, if we see the trend that the higher the reservoir is, the better the algorithm performs, we can just limit ourselves to the top 3 reservoir values when we carry out the combination test, in order to reduce the number of parameters set we have to consider.

Another point we want to consider is that, in the current thesis, we proposed to use Decision Tree, which is a very powerful and commonly used Machine Learning technique. But Decision Tree is not the only Machine Learning technique out there. In the future, we would like to further explore the proposed method using different machine learning techniques, to find out the advantages and disadvantages of each of them, especially in regard to whether it can improve the performance of our algorithm or not.

Last but not least, at the moment we only consider the rebuffering ratio and average bitrate, but in the future we would like to also consider other parameters that can be changed such as join time, buffer size and record what kind of effect they have on the algorithm.

#### **4.4/ Conclusion**

We now make the final conclusions of this thesis based on the result we obtained in chapter 4.2. We have proposed a way to systematically define which parameters set is better than another, and which one will have some tradeoff. With this proposal, we can improve the performance of an ABR algorithm. To achieve more performance increase in the ABR algorithms, we can use our modified decision tree algorithm, leading to further increase of the QoE value by 8.593%, with a majority 98.38% sessions performing better than before. Our modified decision tree algorithm can improve the QoE across various client requirements on different QoE metrics. Furthermore, our algorithm has a low cost both in runtime and space. While the tree building only needs to be done once in a while on the server, the testing algorithm is efficient enough to be run in real time for every client with ignorable negative impact to the user's view experience, such as increased join time.

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